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Arc Mapping: A Critical Review

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Abstract. Arc mapping is a method for graphically documenting a fire pattern which comprises arc marks on the wiring of a structure due to the effects of fire, with the goal of using this information to assist in establishing the area of origin of the fire. The concept was initially presented in 1955, but without any published science (experimental, theoretical, or modeling) basis. By the 1990s, the method was being widely used by fire investigators. Meanwhile, the first paper containing substantive research did not appear until 2005. In this first-ever critical review of the subject, careful consideration of engineering principles and large-scale experimental studies on the subject indicate that the relevance and prominence of arc mapping as a leading indicator of fire origin have been notably overstated. The technique is valid and applicable only in some very limited scenarios. Yet it has seen increased use in recent years by investigators preparing fire reports. In many cases, such attempted use of arc mapping is based on incorrect and invalid hypotheses, which are often implicitly assumed to be true instead of being explicitly stated. Fire patterns are subdivided into directionality (movement) patterns and intensity patterns. Analysis of the research indicates that valid conditions can be expected for use of arc mapping as a directionality indicator in less than 1% of building wiring circuits which sustain arcing. For intensity patterns created by arc sites, propensity is governed by three main variables: fuel loading, ventilation, and burning duration. Only the last is potentially associated with a location being the area of fire origin. But experiments show that fuel and ventilation effects are likely to dominate, instead. In the best-documented study so far, only 23% of arc beads were found to be located near the area of origin, while 61% were found at areas of heavy fuel concentration. This indicates that, in the general case, arc mapping results cannot be used to draw conclusions as to the fire origin. Only in rare cases where it might be demonstrated that fuel concentration or ventilation effects were not governing, would it be possible to use arc mapping results as pointers to the area of fire origin. Since arc mapping is used almost exclusively for forensic purposes, it must be emphasized that methods should not be used, unless it can be demonstrated that they are reliable indicators of what is claimed, and that they are being used properly.

Keywords: Arc mapping, Arc beads, Electrical short circuits, Fire investigation, Metallurgical evidence, NFPA 921

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1. Introduction

Combustion creates exceptionally high temperatures, meanwhile, buildings are not designed as furnaces. Consequently, a building fire is likely to damage various materials in the building. One of the main tools available to fire investigators is to examine the fire effects and consider whether any fire patterns that are formed might provide useful data towards establishing the origin of the fire. In recent years, one type of fire pattern analysis that has received significant usage is arc mapping, i.e., presenting in a diagram the locations at which electrical arcing was observed on energized circuits. It is the purpose of this study to examine critically the science bases determining if and where arcing will occur, along with analyzing all available experimental data published on this question. From this foundation, conclusions are drawn as to when arc mapping uses are valid, i.e., consistent with established science, versus uses of arc mapping which lack a science base, or are based on misunderstanding of scientific principles.

Until the early 1990s, fire investigation was a notably empirical profession, with very limited scientific foundations. As a consequence, various "rules" were used by practitioners, which were later learned to be myths, not valid precepts of science [1–3]. It was already recognized by the mid-1980s that the situation needed to improve, thus in 1985 the National Fire Protection Association (NFPA) established a Technical Committee on Fire Investigations which produced the first edition of NFPA 921—Guide for Fire and Explosion Investigations—in 1992, and updated regularly since then [4]. One of the main tasks of the Committee and the Guide has been to replace myths with science-based procedures. While the origins of arc mapping were in the 1980s, and even earlier, it saw significant usage by the 1990s, and increased further after the 2001 edition of NFPA 921. In its more recent editions, NFPA 921 progressively increased emphasis on arc mapping as a fire investigation tool. However, this was not accompanied by scientific rigor in establishing a clear understanding of its valid uses, versus its limitations and improper uses. Thus, it is important to examine in detail the history of arc mapping and the available experimental validation data, and especially to uncover the underlying hypotheses. It will be shown that some of these, while often tacit and not explicit, are scientifically erroneous or speculative and unsupported, and consequently lead to investigatory conclusions that are not supportable. Recommendations emerge out of this study on improvements for the NFPA 921 treatment of this topic, along with guidance for fire investigators as to what constitutes valid and correct application of arc mapping principles.

The concern about needing a reliable science base is very real, even with the progress that has taken place within NFPA 921. Quite recently, in a study entitled [5] "The Need for a Research Culture in the Forensic Sciences," legal authorities made the bleak conclusion that "forensic sciences in general, and the pattern identification disciplines … in particular, do not currently possess—and absolutely must develop—a well-established scientific foundation." Fire pattern investigation most assuredly falls into this area, and arc mapping in particular. In a similar vein, the National Research Council [6] concluded, "Much more research is needed on the natural variability of burn patterns and damage characteristics." And

even though they did not itemize the categories of burn patterns, it should be clear that electrical arcing patterns are among the important "burn patterns and damage characteristics" which need improving. It is the purpose of this study to examine the extent to which there is a scientific foundation for arc mapping, and the limits to deductions that possess scientific validity.

2. Background

When fire engulfs energized wiring, shorting may occur (but does not necessarily have to). If shorting does occur, a detectable artifact (an "arc bead") will not necessarily be created. Laboratory experiments [7] have found that direct metallic shorting is less likely to create identifiable arc beads than is shorting where part of the path is a carbonaceous material. But the latter is often likely to happen when wire insulation gets burned due to a fire. Furthermore, if an arc bead is created, it will not necessarily be located at the point of first fire damage to the cable.

In fire investigation, arc mapping has been defined in NFPA 921 [8] as "The systematic evaluation of the electrical circuit configuration, spatial relationship of the circuit components, and identification of electrical arc sites to assist in the identification of the area of origin and analysis of the fire's spread." Arc mapping is sometimes also described as *arc surveys*, *arc fault surveys*, *arcing fault pattern analysis*, or similar terms. NFPA 921 first referred to arc mapping in the 2001 edition, which did not provide any procedure details, but simply added arc mapping as the fourth source of information in the Origin Determination chapter. Additional material was developed in the 2004, 2008, and 2011 editions, while the 2014 edition greatly expanded the text and for the first time gave a definition of arc mapping, as indicated above. Changes for the 2017 edition have been minimal.

Note that arc mapping is not related to examining the possibility of arcing as a *cause* of fire. An electrical arc may be the initial event starting a fire, but arc mapping is a method suggested for helping identify the area of fire origin, not its cause. The fire cause is defined by NFPA 921 as: "The circumstances, conditions, or agencies that brought about or resulted in the fire or explosion incident, damage to property resulting from the fire or explosion incident, or bodily injury or loss of life resulting from the fire or explosion incident." In other words, determining fire cause is establishing what took place to enable the fire to occur. Laboratory examination of molten artifacts may be necessary for this purpose, but this is an undertaking different from that of conducting arc mapping and has already been covered elsewhere [9].

Partly due to NFPA 921 providing some emphasis to the technique, arc mapping has become popular in recent years in the investigations of fires in buildings. Numerous instances of this usage have been associated with investigations that are hasty, incomplete, or failing to comport with the requirements of NFPA 921 for conducting a competent investigation. For example, a proper investigation must proceed by determining the fire origin first, only then go on to determining the cause of the fire, and only if these first two steps are correctly completed, may it proceed towards establishing responsibility for the fire [8]. It is improper to deter-

mine responsibility first, then establish the cause of the fire, and from that proceed to identify the origin of the fire.

The present paper examines all of the research published on the topic of arc mapping to date. The most important objective has been to examine the hypotheses put forth by various authors on the principles underlying arc mapping and the ways that arc mapping may be used to assist in determining the origin of a fire. The validity of these hypotheses is then examined in terms of the experimental results and in terms of basic principles of electrical science and fire science.

3. History

The earliest mention of a concept related to arc mapping is found in a 1955 book by Straeter and Crawford [10]. The authors suggested that: "Condition of wiring after the fire. The amount of destruction of insulation on electric wires can reveal a clear pattern for the area of intense heat. Electric shorts have their physical effects. Investigate to be sure whether the short caused the fire or the fire caused the short. The exact locations of the centers of wire damage, of char, and of other indications may well be compared to answer this question." And: "Sequence of shorted electric circuits. The appliances that were stopped by electrical failure may indicate the path of the fire to some degree, especially in a larger building in which there are many circuits and they were put out one at a time. The times at which the clocks stopped could tell which circuits were included first in the fire's path." The next development was in Japan, where in 1968 Miyake discussed arc evidence at a closed meeting on forensic engineering held by the National Research Institute of Police Science. He then published it in a journal in 1975 [11], stating: "If two points of severing due to shorts are found on an electric cable burned in a fire, it means that the farther point from the power source was damaged by the fire earlier than the other one. This can be used to estimate the place of origin."

The obscure 1955 and 1975 references were evidently not seen by later workers and, in most literature, the first reference is to a 1983 paper by Delplace and Vos [12], who stated that they had been developing for 12 years a method that they called "systematic mapping of the locations of short circuits." The paper was brief and provided only a single diagram (Fig. 1), but it can form the starting point of the present study, since they proposed testable hypotheses how arc mapping might be interpreted. The basic Delplace and Vos hypotheses were:

- "A close parallel exists between the patterns left by combustion and the location of short circuits."
- "A short circuit will normally take place wherever the fire first damages the cable. This gives us the point along the entire length of the circuit earliest affected by the fire."

They also noted that, when several sever-arcs are found on a particular circuit, the earliest one had to be the farthest downstream from the power source, since

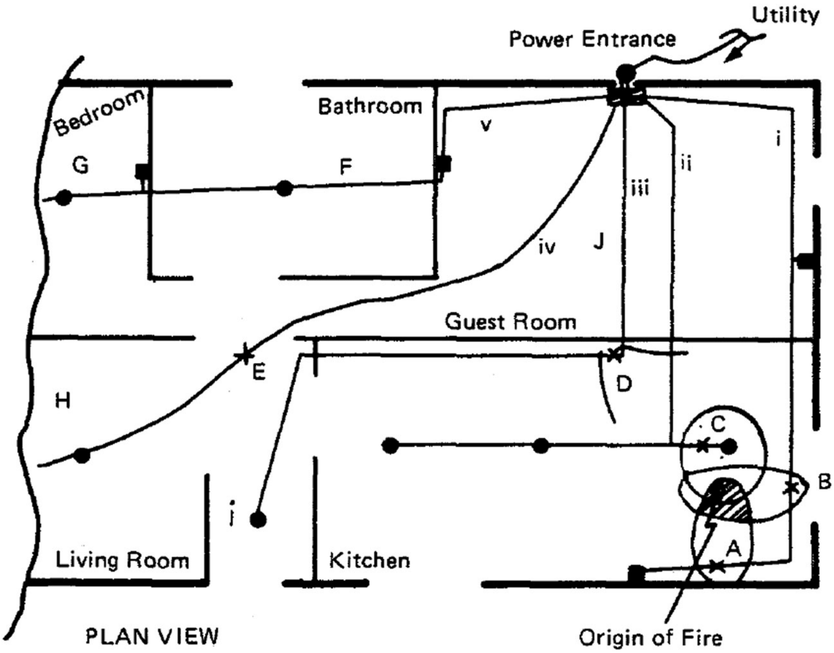

Figure 1. The diagram published by Delplace and Vos [12]; the arc map is hypothetical and is not based on any experimental research.

the initial sever-arc removes power from the downstream portion, but not the upstream portion. (Note that a sever-arc is an arcing location where one or more conductors involved have been severed by action of electrical arcing, that is, the conductor in question is no longer continuous at that location). They then offered a hypothetical example of a vehicle fire, which they also considered to be amenable to this analysis: "If damage by electric arcs is found at the dome light and at the steering wheel, then the fire did not start in the engine compartment, nor in the dashboard." The paper gave no details of any experiments or analyses that might have been conducted, and the method saw little use during the later 1980s and early 1990s, apart from one other forensic paper [13] and the teachings of Robert Svare. Svare is an engineer who taught the technique to numerous individuals in classes on fire investigation, but published only brief summaries [14, 15] (Fig. 2). Interest within the profession increased in the late 1990s, after which a number of papers appeared.

In this review, emphasis is placed on the hypotheses contained in the Delplace and Vos paper. The reason is that this is one of the few published references where the authors endeavored to actually make the underlying hypotheses explicit. Most subsequent authors either tacitly agreed with Delplace and Vos, or else failed to provide explicit hypotheses for other reasons; however, hypotheses proposed by other authors are also considered.

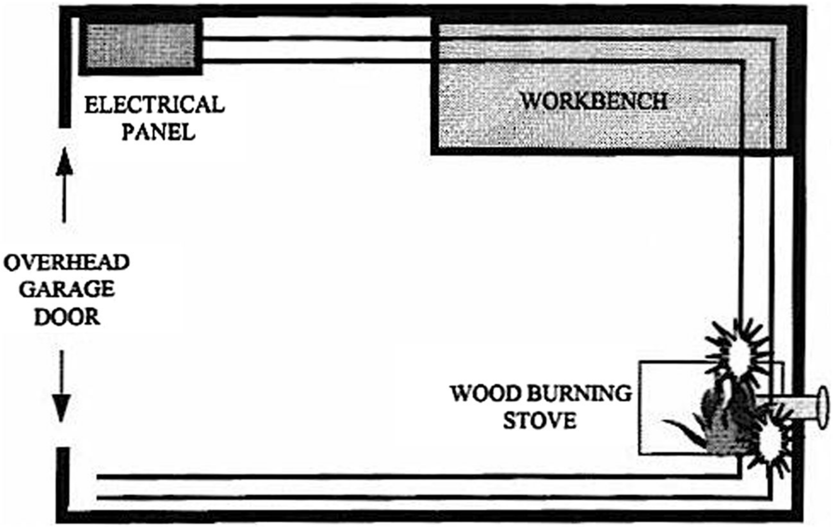

Figure 2. Teaching illustration used by Svare in a 1995 paper. According to the author, this arcing evidence signifies that fire originated at the wood-burning stove. This map is also not identified as being the outcome of any experimental research. Diagram: Robert Svare.

4. Technique

Procedurally, arc mapping is simple. A floor plan (a "map") is made that, if not of the whole structure, encompasses at least all areas potentially likely to be the area of origin. All circuits running through the area need to be traced [16]. The wiring then is inspected for presence of arcs, and those are recorded on the floor plan.

Arc mapping is likely to be a tedious process. Unless most of the structure can be excluded on the basis of other considerations, a great deal of wiring may need to be examined. But the examination is likely to be slow, since arc beads can be small and may require use of bare fingers or a sliding a cotton ball in order to detect some of them [17, 18]. However, it was also learned that the cotton ball technique does not have value unless charred insulation material is first thoroughly cleaned off conductors; otherwise, cotton balls tend to get stuck on charred debris [19]. For stranded wires, this can be difficult, and ultrasonic cleaning is likely to be needed [19]. In addition, even prior to making this search, it is necessary to trace the relevant circuits [16] (back to a specific circuit breaker in the load center) and in itself this is likely to be a laborious process (and may be impossible if the conductors are broken).

Even though it is sometimes done by electrical or forensic engineers, arc mapping does not require engineering expertise. The only electrical knowledge needed by the individual doing the work is to know the configuration of electrical power cables and the identification of the closed/open/tripped status of circuit breakers.

Thus, arc mapping can be done by a competent fire investigator or assistant [20]. Note however that a tripped circuit breaker does not necessarily indicate tripping due to fire-caused short-circuiting. Circuit breakers may have tripped from unrelated causes, prior to the fire, or tripped due to ambient heating of the circuit breaker itself by the fire [21].

5. Governing Principles

The Delplace/Vos hypotheses can be usefully examined as a starting point. The first hypothesis (*A close parallel exists between the patterns left by combustion and the location of short circuits)* does not follow from any principles of science. However, its validity may be examined by experimental study, since hypotheses for which there is a preponderance of supporting experimental evidence may also be accepted as true. As will be seen later, experimental evidence indicates that it indeed is true, but it is not helpful towards establishing the origin of the fire. The likelihood of arcing is indeed the highest in places of most concerted burning. But, as will also be shown, at any particular location, the intensity of fire damage is more likely to be controlled by fuel concentration or by ventilation effects, than by duration of burning (the longest-burning area is likely to be the area of origin).

The second Delplace/Vos hypothesis (*A short circuit will normally take place wherever the fire first damages the cable. This gives us the point along the entire length of the circuit earliest affected by the fire*.) needs some detailed scrutiny. The first sentence is either untrue, or a truism. If "first shorts out" is taken as synonymous with "first damages," then it is a truism, making the statement superfluous. But if it is understood that "damage" can entail degrees of severity and is not identical to "shorting," then the sentence is not a general truth. If the fire first causes mild thermal damage that does not result in shorting, then it is incorrect to state "a short circuit will normally take place." Now, consider the second sentence, which, reworded more explicitly, would say that "On any particular circuit, a found arc bead will denote the first place where flames impinged on this circuit." There is no principle of fire science or electrical science that would make this true (or false) for all possible fire scenarios. Potentially, it might be true in a probabilistic sense; it would then be amenable to experimental demonstration, which is considered below. To give the authors the benefit of the doubt, it may be that they were endeavoring to capture a concept similar to that subsequently espoused by Carey, which is considered next.

Carey et al. [27] proposed the following hypothesis for arc mapping theory: "Relating the position of the beads that are formed due to arcing with the layout of the electrical system can help establish the area where the fire first attacked the energized electrical system." First, it may be noted that the authors take a weak position: "can help" indicates that, at best, they are anticipating some correlation, rather than describing facts provable from known science. The implied view here is that arcing will line up around some boundary of flaming at some unspecified early time of fire growth. Carey, in fact, put forth such an explicit hypothesis (beading will be "found on the edge of the initial plumes") in his 1999 paper [49],

but his later work did not support it (nor did any other researcher's). Similarly, Churchward et al. [22] hypothesized that: "arcing sites will pattern themselves about the area of origin," while Johnson and Rich [23] hypothesized that "arc mapping [will] … create a boundary around the area of origin." Taken together, the above hypotheses may more succinctly and clearly be worded as:

- Arc sites will be primarily found only in the area of fire origin;

  and, possibly:

- Arc sites will be primarily found around the periphery of the area of early fire involvement.

Observe that, thus far, nothing has been said about loss of power to circuits. Yet, fire investigators sometimes consider that this is an important reason why arc mapping might be a viable technique for identifying the area of origin of a fire. In this regards, relatively clear hypotheses were put forth by Karasinski et al. [24]:

- Initial stages of fire progression
  - Will cause arcing on energized circuits
  - Arcing will typically cause circuits to be de-energized by opening protective devices (breakers, fuses) or severing conductors.

- Later stages of fire progression
  - Further away from the area of origin, there will remain fewer energized circuits, and therefore less arcing.

This series of hypotheses introduces a new element to consider—progressive loss of power to circuits—while still espousing the same conclusion: arc beads will be copious near the origin, but scarce farther away.

From fundamental principles, it is useful to consider what can be accepted to be true, solely on the basis of accepted fire science or electrical science:

1. An arc bead can only be created if the circuit is powered at the time that it gets fire engulfed and shorted. (But also note that, in some cases, power may be supplied by a flow path that is not the normal one. For example, this can entail back-feeding of a dead circuit through shorting with a still-live one, or operation of an alternate power supply such as a generator or an uninterruptible power supply, UPS);
2. Arc beads will not be found on circuits that were de-energized at the time of fire engulfment, irrespective of whether the loss of power was due to tripping of circuit breakers from earlier arcing, severing of conductors due to arcing elsewhere, manual disconnection, or utility outage;
3. Arc beads are likely (but not guaranteed) to be plentiful in areas where sustained flaming occurred while power was still available; and

4. Arc beads will not be found on circuits where fire exposure was mild.

The latter two statements stem from the well-accepted facts that applying flames onto energized conductors can burn the insulation off them (in full or in part). Then, conductors with damaged or destroyed insulation and without special means of separation and securement **may** make contact and thereby short out. Energized conductors with damaged insulation may also short out to non-electrical grounded objects. Note that this says nothing about the origin of the fire.

How can then the scheme be applied to fire origin determination? By making an additional hypothesis:

5. Electric power will be available in the area near the fire origin, but will no longer be available once flame spread has progressed away from the origin.

There is clearly no principle of science that requires the latter to be true. So next, it must be considered how power becomes lost in structure fires. Several ways are possible:

- *Tripping of Circuit Breakers* Shorting may trip a circuit breaker (or open a fuse), but the actual outcome is probabilistic and depends on voltage, available short-circuit current, characteristics of the circuit breaker, and other details of the circuit. Note: if arcing causes conductors to get *welded* together, tripping can be almost certainly assured, provided the conductor size is consistent with the circuit breaker rating and the circuit breaker is not defective. But in some cases, prolonged arcing can occur, and wires may undergo welding without tripping of circuit breakers, if the size of the wires is small compared to the circuit breaker rating.
- *Severing of Conductors* An initial arc may or may not trip a circuit breaker, and it may or may not sever an energized conductor. But if an energized conductor does get severed, no arcing will be possible downstream, although it may remain possible upstream of the sever point. However, no methods exist for calculating if a given event will, or will not sever a conductor, nor which one will get severed if severing occurs. These are probabilistic events. (Note that severing a ground or neutral conductor will not necessarily de-energize the circuit, since arcing can still potentially occur between a live conductor and another conductor that is not at the same potential as the severed conductor.)
- *Manual Intervention* Building occupants generally do not respond to fires by turning off electrical circuits, although this may occasionally happen when a fire is seen to be electrical in nature. Standard operating procedures at fire departments vary widely. But fire departments may not shut down electric power unless and until a fire has become large or difficult to control. By that time, fire will have spread greatly beyond the area of origin. Thus, manual intervention is likely to occur only later in the progression of a fire, when fire has progressed greatly beyond any areas potentially to be evaluated as area of origin.
- *Utility Power Outage* While this will rarely be an issue, power may simply cease to be available due to a utility outage, unrelated to any of the above actions.

Thus, apart from manual intervention (where timing may sometimes be estimated), or unrelated power outage (which would be exceptionally rare to coincide with a fire event), de-energizing of circuits in a structure fire has to be considered as probabilistic. Given that, it becomes evident that the potential of arc mapping to reveal anything about the area of fire origin is fundamentally probabilistic, and only a sufficient ensemble of experiments can establish the potential validity of the technique. (However, certain deductions involving severed or tripped circuits may sometimes be made reliably, and these possibilities are considered later.)

The discussion to this point focused solely on establishing a fire origin area smaller than a whole room, assuming the origin is known to be in a particular room. But Carey [49] hypothesized that arc mapping can also "be used effectively at large fire scenes to identify which compartment the fire started in." No research exists on this point, but it is useful to consider the layout of electrical circuits in buildings. Assuming that manual intervention or power outage does not occur, the only way that circuits will be de-energized in regions remote from the area of active burning is by severing of conductors or tripping of circuit breakers. But this will be possible *only if the same circuit's wiring extends from early-burning areas to a remote area in question*. Assuming this is not ancient wiring (where the circuits in a building were typically very few), this is unlikely. Modern buildings in North America are commonly wired so that one circuit will serve only a single room, or a few closely-situated rooms or spaces. If that is the case, then there is no physical reason de-energizing of circuits remote from the area of active burning should be expected. (Note that, in the UK, it is common to use 'ring mains.' This entails larger-size branch circuit conductors, with the cable run so as to make a loop, fed from the same circuit breaker at both ends. Such ring mains may traverse sizable areas.)

6. Experimental Validation

As seen above, no principle of science establishes that areas far away from the point of origin will be de-energized and, therefore, bereft of arc beads if fire extends into those areas. But closer to the area of origin, will arc beads preferentially occur near the origin on any particular circuit, as opposed to further away? Assuming the initial fire is localized (as contrasted, say, to a vapor cloud ignition), heat fluxes might be expected to decrease monotonically with distance from the fire. Thus, with all else being the same, it might be surmised that arcing would necessarily occur first closest to the fire, and only later additional arcing might occur at farther locations. As will be shown later, the assumption of heat fluxes monotonically diminishing with distance will rarely be valid for real building fires. Apart from the dominant role of local fuel load and local ventilation effects, there are some cable-related reasons why wire shorting potential is *not* likely to bear any simple relation to distance from fire origin:

- The elevation of the cable may change along the run

- There may be more or less thermal protection at various locations along the run
- The stresses in the cable may favor shorting at some locations.

The last factor needs some explanation. Burning away plastic insulation does not, by itself, cause shorting. For shorting to occur, either conductors that are initially a few millimeters apart must move into contact, or else shorting has to involve a carbonized insulation bridge. The propensity for conductors to come into contact will be influenced, among other things, by local stresses (bends, kinks, twists, etc.) of the conductors. Once plastic is burned away, conductors may stay in place, or move apart, or move closer together. None of these factors above can be calculated to predict the shorting history of a cable. Shorting may also proceed without metallic contact, due to carbonized insulation bridging the conductors; issues related to this have been discussed by Babrauskas [25]. In view of the above issues—which are not amenable to current-day theoretical or computational analysis—it is important to examine the results of experimental programs.

The earliest studies on this topic, discussed above, contained no test data. In 1986, Rothschild [13] published a paper describing his investigation experience, but also provided no experimental results. The first report giving experimental data was provided by Carey [26] in 1999. In his first room burn, he found two arc beads, one near the area of origin, the second near a window 3 m away. For a repeat burn, two arc beads were found, both in the general vicinity of fire origin. Carey also conducted another burn, but this was not for the purpose of validating arc mapping. In 2003, Carey supplemented this by another test burn [27] where he found 6 arc beads in the test compartment, 3 close to the origin and 3 at the opposite end of the room. He concluded "the research has found that the arc mapping methodology has proven to be a reliable indicator of the fire's areas of origin." This conclusion, however, was not justified by the data, since clearly there were as many arc beads remote from the origin, as close to it, in both his first and his last tests.

Carey's studies were internal reports or conference lectures and were little-known in the profession. The first published and widely-known experimental study was presented in 2005 by West and Reiter [28], who reported on three full-scale room fire tests (Fig. 3 shows the detailed results for their third test). In each test, 12 to 15 branch circuits were installed using 14/2 NM cables. These were attached to the ceiling and allowed direct fire impingement. Despite the fact that the tests were run with wiring strung in the open, along the ceiling, in none of the three tests was the arcing clearly localized to the area of origin. While in all cases there was arcing near the area of origin, arcing was also found remote from the area of origin (in some cases, diametrically opposite). For test No. 3 shown in Fig. 3, the authors themselves observed that electrical arcing activity was "greatly influenced by the entrained air velocity," that is, by the ventilation flow patterns. Furthermore, in all three tests, the point of ignition was on the sofa, which was, by far, the predominant fuel load item in the test rooms. Thus, the reason for somewhat greater concentration of arc beads in the vicinity of the sofa was likely a fuel load, not a fire origin, effect.

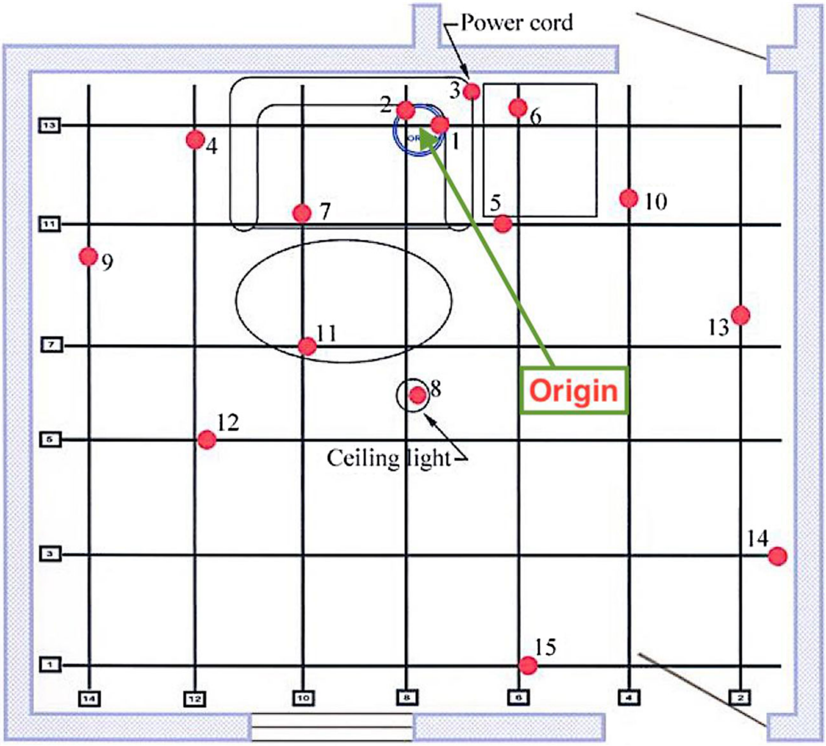

Figure 3. Arcing locations (red dots) found by West and Reiter for their test No. 3; ignition was on the seat of the two-seater couch. Copyright Interscience Communications Ltd, used by permission (Color figure online).

The largest study of arc mapping was published in 2009 by Carey [16], who conducted 39 compartment burns. This is an order of magnitude greater than presented by any other researcher. However, most of the research was focused on metallurgical studies and only limited conclusions can be drawn from the arc mapping work. The main limitations were: (a) only a single room was studied; the ability of arc mapping to identify the room of fire origin was thus not possible to address; (b) only 4 circuits were used, yet the rooms were notably large; (c) all wiring was run exposed on the ceiling; no protected or low-level circuits were studied; (d) most of the fires were exceptionally fast, flammable-liquid fires, with circuit breakers tripping in 2–3 min, and sometimes even around 1 min. Furthermore, 17 of the 39 tests involved scenarios with multiple points of ignition (used to study incendiarism indicators), thus there were only 22 tests where a fire with a single point of origin was configured, consequently only these 22 tests can be used for analyzing arc mapping.

Carey concluded "Analysis of the three-dimensional data recorded during the experiments and the arcing events has indicated that there is a high probability of arcing damage occurring to electrical conductors located close to the fire's area of origin." This would not be helpful for validation purposes, since the author does not further specify that a paucity of arcing is found in areas not close to the area of origin. But an analysis by this author of Carey's data is provided in Appendix 1, where the arc locations were categorized as being near the area of origin, near a local fuel concentration, near a ventilation source, or elsewhere (none of the above). It may be noted that, apart from beads found 'elsewhere,' the categories are not exclusive. Thus, for instance, bead might be found near the area of origin, but if that area is also near a ventilation source, it would be additionally tallied as being near a ventilation source. The analysis indicated that the presence of an arc bead is nearly three times as likely to denote an area of fuel concentration as it is likely to correspond to the area of fire origin. In addition, an arc bead is more than twice as likely to be found in an area of localized ventilation, as it is near the fire origin. This plainly indicates that *arc beads will not preferentially be found near the area of fire origin.*

Wood and Kimball [29] conducted 4 full-scale fire tests in a 3.7 m $\times$ 4.9 m fully furnished bedroom. An array of 14 AWG NM cables was attached to ceiling on a 0.61 $\times$ 0.61 m grid; each cable fed by a separate 15 A circuit breaker. While such close spacing will generally not simulate real-life conditions, it does enable arcing locations to be better assessed than the coarse spacings used by Carey. No loads were fed from the cables. In each test, all circuit breakers opened before the fire reached flashover stage. Arcs found were typically between hot and ground, but there were some arcs between all three conductors. In most cases, they found that the arcing artifacts were very small (1–4 mm) and required concerted effort to locate. The main conclusion that they drew from their work was that arcing is likely to occur in the room of fire origin, but "no arc mapping patterns emerged from the room fire tests to clearly indicate a point of origin." But they also added "all conductors did arc indicating that the conductors may reliably indicate a room or area of origin even in the absence of being able to indicate a point of origin." The latter conclusion is incorrect, since if arcing (or even copious arcing) suffices to establish the room or area of origin, then buildings with widespread, extensive arcing would necessarily have been victims of multiple areas of origin, which is an unjustifiable conclusion. It bears emphasis that the authors did not run any tests where arcing on the wiring of multiple rooms in a building was studied.

Up to this point, all experimental studies involved NM cables simply fastened to the bottom of a gypsum wallboard ceiling. This may simulate exposed wiring in unfinished basements or attics, but is not representative of normal wiring conditions in occupied spaces. In 2015, Wheeler [30] was the first researcher to explore experimentally the effect of protective barriers. He conducted three burn room tests using 14 AWG NM cables that were run up one wall, across the ceiling, and down the opposite wall. In test No. 1, the NM cables had no protection. In test No. 2, the cables on the ceiling and on one wall were protected by $\frac{1}{2}$-in

(12.7 mm) thick gypsum wallboard, while the cables on the other wall were protected by thin, 1/8-in (3.2 mm) thick wood paneling. In test No. 3, all cables were protected by $^{1}/_{2}$-in gypsum wallboard, ignition was on the floor near a chair (Fig. 4), and the fire went through flashover before being extinguished. The results (Fig. 5) do not validate the ability of arc mapping to localize an area of origin that is smaller than room-size. Wheeler provided some moderately optimistic conclusions from his tests that were not justified by the data, but for the protected test (No. 3), the results indicate that *arcing was localized to the area of heaviest fuel concentration (the sofa), rather than the area of origin*. It should be noted that even Wheeler's protected experiment—which is the most realistically configured experiment reported to date—did not involve wiring compliant with the electrical code. Sec. 300.4 of the NEC [31] requires that wiring behind a wallboard inside walls have at least a 32 mm (1.25-in) air space between the cable and the back of the wallboard., while Wheeler's gypsumboard was installed directly against the wiring.

7. Multiplicity of Arcs

Some investigators used to believe that multiple arcing will not occur on a single circuit, but well-known forensic electrical engineer Bernstein [32] already noted in 1991 that multiple arcs are possible. Rothschild [13] reported finding as many as 4

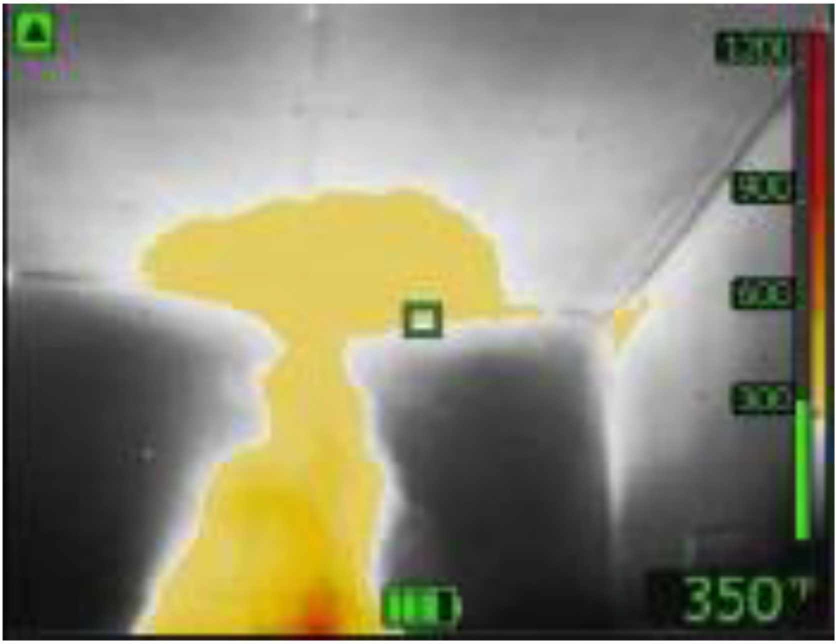

Figure 4. Thermal-imaging camera view of Wheeler's Test No. 3, showing early stages of fire impingement on the ceiling above the ignition location (chair).

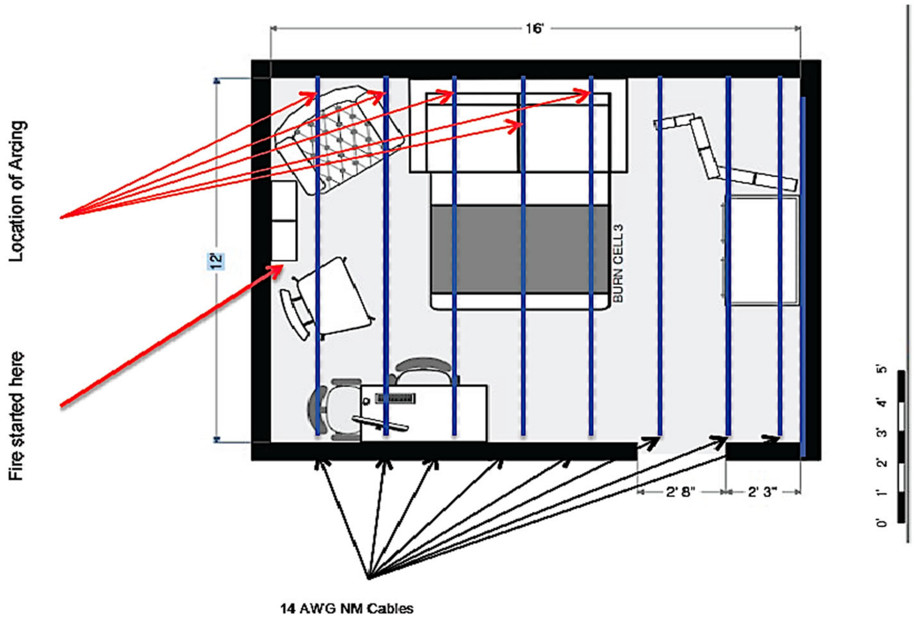

Figure 5. Results from Wheeler's Test No. 3 (all cables protected by 1/2-in gypsum wallboard). Diagram: David M. Wheeler.

arcs on one 14 AWG branch circuit, but provided no details. West and Reiter [28] provided the first detailed experimental results on multiple arcs on a single circuit, and Table 1 shows their results: 4.8% of the circuits experienced two arcs and no instances of more than two arcs were found. Carey [16] found that 5.8% of his circuits experienced two arcs (and none three or more). Since these two studies were done using substantially different test arrangements, yet gave similar results, it can be concluded that the finding has generality: About 5% of solid-core conductor circuits can be expected to show two arcs, and an insignificant fraction may exhibit a larger number.

8. Arc Bead Type and Size

In his tests, Carey [16] found that 29% of arc sites constituted sever-arcs, while 7% were welded together. For arc sites where severing was found, however, he did not document the fraction where the hot conductor was severed.

Table 1
Results From Tests by West and Reiter on Fire-Induced Arcing of 14/2 NM Cables

Test no.	Test 1	Test 2	Test 3
Circuits with one arc	11	14	15
Circuits with two arcs	1	1	0

West and Reiter [28] analyzed their data for arc bead size, and found beads ranging from very large to barely perceptible. They noted that this was an unexpected finding, since the circuit breakers were identical for all circuits, as was the available short-circuit current, I_{sc}, of 310–320 A. These findings indicate that arc bead size is a highly probabilistic quantity. However, there are some known effects on bead size, and Ablenas and Bodzay [7] demonstrated that lower short-circuit currents are more likely to result in large arc beads, than if the current is high and rapid circuit breaker tripping occurs. In their study, Ablenas and Bodzay found that, in fires, the short-circuit current is likely to be much lower than I_{sc}, due to shorting occurring with carbonaceous material in the path, not a direct metal-to-metal contact.

9. Arcing with Stranded Wires

Branch circuits in 15 or 20 A ratings in North America use solid-core copper wires. But power cords and wiring inside appliances and equipment are likely to use stranded wires. Stranded wires can behave differently from power cables having solid-core conductors for several reasons:

(a) Stranded-wire cords are typically used exposed in the room, not protected by any thermal barrier. Stranded appliance wiring may be protected by an appliance housing, especially if it is steel, but is unlikely to be located behind a gypsum wallboard barrier.
(b) Power cords are likely to be low, or at floor level, as opposed to being high or at ceiling level.
(c) Most stranded cords use only a single layer of insulation, rather than having both wire insulation and a jacket.
(d) Stranded-wire cords are likely to use much smaller size conductors than cords used for building wiring purposes; consequently, overcurrent protection may be much less effective, and multiple arc sites on a single circuit might be readily expected.

Thus, experimental data obtained on solid-conductor power cables may not necessarily directly apply to stranded power cords, and results specific to stranded wires should be considered. In an early paper, Rothschild [13] described a fire where 7 arcs were found on one power cord. Hoffmann et al. [33] conducted a laboratory study on appliance power cords that had 18 AWG copper conductors. A large number of tests (713) were run under several thermal conditions—radiant heating, small gas flame, and a more realistic fire from a small wood crib. The results indicated that 100% of the power cords attacked by a wood crib fire showed arcing damage, while lesser fractions of specimens receiving radiant heat or small burner flames shorted. Johnson and Rich [34, 35] ran a single compartment test where they exposed to a room fire an extension cord and three appliance cords plugged into it, arranged at heights ranging from floor to table height. The extension cord was extra-heavy duty (12 AWG) and was powered from a 20

A circuit breaker. The compartment went through flashover, and then was extinguished shortly thereafter. The extension cord showed 4 arcs, one appliance cord had 4 arcs, a second had "multiple" arc marks, while the last one had none. Presumably the extension cord shorted out and severed or tripped the circuit breaker (the authors did not state), thereby de-energizing the last appliance that showed no shorting. The authors also reported a fire case where three appliances were plugged into a circuit-breaker protected power strip. The power strip's cord showed arcing, as did one appliance, but not the other two. In this case, it was found that the power strip's circuit breaker did trip. It can be concluded from this that the likelihood of arcing on power cords is decreased if they are fed by a power strip or an extension cord, since upstream shorting or tripping may act to de-energize plugged in devices. Otherwise, the likelihood is high that energized, stranded cords will get shorted out in a serious room fire, but it should not be inferred that this is a necessary outcome.

Hoffmann et al. [36] also ran room fire tests with energized appliances and showed that fire attack on power cords will often, but not always trip circuit breakers. In some cases, arcing damage to cords occurs, but the affected circuit breaker was not tripped. Hazelwood [37] reported a case where a long extension cord was found to have not only 4 arc locations, but each location was a sever-arc. Such evidence does allow the direction of arcing damage to be established, which necessarily had to progress from the downstream to the upstream end of the cord.

Stahl and Parrott [38] discussed the application of arc mapping to motor vehicles. Vehicles utilize primarily stranded conductors, but also differ from building wiring in the power supply: DC supplied typically at 12 V for passenger vehicles, with higher voltages for heavy vehicles or electric cars. They did no tests, but did give a number of warnings against misuse of the technique for fire investigation in motor vehicles. Their main conclusion was that, given an absence of any laboratory studies applied to motor vehicles, arc mapping cannot be assumed to be a "dependable, robust technique when translated from structures to vehicles and equipment."

Lancaster and Meadors [19] studied arc mapping of stranded conductors using three test rooms, fueled by burning wood pallets. Fire was extinguished in the first one after all circuits tripped, while the next two rooms were allowed to burn to the ground. Each test used a number of stranded cords laid out along the floor. Trip times were typically 10 min, as contrasted to 2–3 min for solid-core cables stretched across the ceiling in Carey's tests. The work was unfinished, however, and the authors only presented metallurgical results, but not data obtained from the arc mapping itself.

Shanley [39] described using arc mapping as an aid in analyzing a clothes dryer fire, specifically to determine if the fire originated inside the appliance, or outside. No tests were run, and Shanley simply concluded that the fire originated inside, since the heater was energized, and since arcing locations did not correspond to places that would be most vulnerable to fire attack from the outside. Kovarsky [40] also did not perform tests, but reported investigation conclusions from several types of cases, which are generalized and expanded here:

- Arcing was found on the wiring inside an appliance at a location well away from external fire attack, and this is taken to indicate that fire originated internally, near this arcing locale. This scenario is innately questionable, since a fire originating inside an appliance is unlikely to then jump to far-off areas while leaving the near environs of the appliance unburned.
- The preceding scenario is narrowed to specify that, in addition, no arcing is found elsewhere inside the appliance, closer to the external fire. Again, this is a questionable scenario. More likely, a small, self-terminated fire occurred inside the appliance unrelated to the structure fire being investigated.
- Arcing was found inside the appliance at a location close to where an external fire would likely impinge on the device, but far from likely sources of ignition inside the appliance. Kovarsky considered that this allows one to conclude the fire originated externally. However, as discussed below, Hoffmann et al. showed that arcing inside an appliance from an external fire may more frequently be located near the externally heated area, but there is no reliable correlation. Thus, conclusions should not be drawn solely on the basis of distance between the external thermal attack and the location of internal arcing.
- Arcing is found on the cord or plug of the appliance, but no arcing is found inside. Kovarsky considers that this rules out the hypothesis of fire originating inside the appliance. However, this is not a valid deduction from general principles of science, and by itself such a condition does not preclude the origin of the fire being inside the appliance. A fire originating inside the appliance may create arcing close to the origin, inside the appliance, but this is not required. Fire may originate internally at a bad connection or an overheated component, but at a place where wiring cannot readily short out and arc. In such a case, it may well be possible for fire to emerge from the appliance and attack a nearby cord or plug outside. However, any arcing found inside an appliance warrants a detailed laboratory examination of the item.

Hoffmann et al. [41] conducted a test to examine the question whether arcing may occur inside appliances due to an external fire. They set up a single room test where three appliances—a refrigerator, a dishwasher, and a clothes dryer—were exposed to the room fire that was started in a trashcan. The dishwasher showed arc damage at several locations inside the appliance. The refrigerator showed arcing to three different internal circuits, but all close to the same general location. The dryer showed arcing on its power cord and at five different locations in its internal wiring. Two of the 5 locations were near the back of the unit, far away from the room fire that was in front of the appliance. These results indicate that an external fire can readily cause arcing inside energized appliances, but does not support the notion that arcing necessarily will be confined to portions of the interior most directly proximate to the external fire attack. In some cases, external fire attack may be close to the front of an appliance, but internal shorting may occur due to radiant heating from overhead.

The correct conclusion with regards to appliance wiring is that the same principles are obeyed as for room fires. The propensity to arc is related to the propensity for thermal damage, but the latter is controlled by fuel arrangements and

ventilation patterns, and not just by time elapsed from start of flaming at a given location.

Hoffmann [42] also presented a scenario where two appliance cords are plugged into an outlet, the circuit breaker has tripped, but only one cord shows arcing (but *not* welded together). Hoffmann suggests that the appliance whose cord does not show arcing can be ruled out as being the origin of the fire. In some cases, an engineering analysis may demonstrate that this is likely to be true, but no fundamental science principles require it to be so. Burning of fuel packages commonly occurs so that, if flames are going to cause cord shorting, this will occur first to the cord of the equipment burning, rather than to a cord of neighboring equipment. But arrangements can also be such that the converse will be true. Thus, a general behavior cannot be assumed in the absence of a specific engineering analysis.

10. The Role of Protective Devices

Some additional considerations are pertinent to situations where there is some form of circuit protection downstream of the load center. One example consists of outlets with built-in GFCI (ground fault circuit interrupter) or AFCI (arc fault circuit interrupter) protection. This protection may be readily triggered by fire conditions downstream of the protected outlet. The tripping action will not remove power from the wiring upstream of the outlet, thus, additional later faulting might occur on the run between the load center and the outlet. Goodson et al. [43, 44] described some cautions in analyzing this scenario.

Certain appliances are equipped with internal or plug-mounted fuse protection (or, occasionally, circuit breaker protection). Does the blowing of the fuse, or the fact that the fuse is intact, indicate anything about the origin of the fire? Kovarsky [40] correctly explained that, in general, no conclusions can be drawn beyond the trivial one that that if a fuse blew due to overcurrent then the appliance was energized at some time prior or during a fire. Note that even the time period for this cannot be established. A fuse may have blown some time prior to, and unrelated to the fire. Methods exist to distinguish fuses melted from overcurrent versus due to external fire heating however [45, 46].

11. Erroneous Concepts

Any concepts associated with arc mapping practice can be rejected without need for considering experimental results or validation, if they are based on an incorrect understanding of electrical science. One such incorrect principle has been succinctly expressed as [47]: ‘‘A basis for arc mapping is the idea that on any given circuit, electrical activity that is furthest from the electrical source (e.g., panel box) occurred prior to activity that is closer to the electrical source.’’ The concept was first enunciated by Rothschild [13], then later presented by others [14, 40, 48, 49]. But the early researchers Miyake [11] and Delplace and Vos [12] correctly understood that this is not a general conclusion but only holds if there is a sever-arc—-

then any electrical activity after that must be upstream of the severing location. And Bernstein [32] explained that: "The arcing farthest from the power source probably occurred first *if arcing closer to the power source caused conductors to separate*." This follows from simple continuity, since current cannot flow beyond a severed place and therefore arcing cannot take place [50].

Recent authors have generally not explained the basis for their erroneous conception, but Rothschild made his basis clear: he did not differentiate between a bolted short and an arcing short, and thought that, once a short occurs, this means that no current is available to flow downstream of that point. In fact, arcing shorts on 120 VAC, and even 240 VAC, circuits are brief even when a circuit breaker is not tripped [51]. The arc may self-extinguish during the next zero-crossing of the current. But magnetic forces tend to push the conductors apart [52], aided by flow of molten material. Thus, an arcing short is likely to clear itself and, if the circuit breaker has not tripped and conductor severing has not occurred, the circuit is able to carry current further downstream. Rothschild did correctly point out that, when shorting occurs, current in the conductors upstream will necessarily increase, and this increased current may lead to arcing failures upstream. In another early paper, Sanderson [48] thought that arcing further downstream from the original arc cannot take place since all arcs will be sever-arcs, but this is also not correct.

Recently, the Bureau of Alcohol, Tobacco, Firearms and Explosives [53] (ATF) published a description of an arc mapping method that they apparently had been teaching at in-house classes, although they had not published it previously. According to their description, after an arc map is prepared, two ellipses are to be drawn, one encircling all arc points found on circuits running left–right, and a second one encircling arc points on circuits running top-down on the map. Once this is done, the origin of the fire will be found in the area where the two ellipses overlap. They then claimed that the tests by West and Reiter [28], when plotted this way, showed that the point of origin will be within the ellipse 'overlap' area. This notion is not supported by any principles of accepted science, nor does it comport with experimental findings, aside from those specially-selected for this purpose.

If all that was required for a method to be valid is that it correctly predict the results of a single set of tests, let the following empirical assumption be made: The origin of the fire will be found to be along the center of the wall most remote from the room's doorway, and located 0.5 m in front of it. Comparing against the three West/Reiter tests, it will be seen that this rule predicts precisely and unequivocally the location of the fire origin in all three of them. In fact, of course, such an empirical rule would not be valid, since it would pertain only to the West/Reiter tests and would not have relevance to other fire situations.

In addition, the notion of a regular grid of wires being found in any room where an actual fire occurred is exceedingly low. But assuming the wires are not embedded in some sort of gas-deflecting obstructions, arcing potential at any location cannot have any possible connection on whether the wires were run N-S or E-W. Furthermore, while West and Reiter made important contributions to the state of art in a number of areas, according to current knowledge, their room

setup was biased. In all three of their tests, the point of fire origin coincided with the location of the heaviest fuel load package. Since fuel load is one of the main factors governing the potential for arcing, placing the origin at the location of the heaviest fuel confounds the fuel-load and fire-origin variables, not allowing them to be unraveled. Even with that bias, however, their results showed a remarkable propensity for arcing at places far away from the ignition point, often near the open doorway. In addition, their experiments were conducted before it was realized that running wiring below the ceiling membrane, rather than above it, prejudices the outcome of the testing, if the end-use environment is the one most commonly encountered—wires concealed behind wallboard.

In the most recent test series, Wheeler [28] realized both of these problems, thus in his test No. 3 the cables were protected behind gypsum wallboard. Figure 6 shows the test results with an ellipse drawn per ATF suggestion. First, it is clear that only one ellipse can be drawn, not two, since there were no cables running in the perpendicular direction. More importantly, it can be seen that not only does the point of fire origin *not* fall inside the ellipse, it is located in another part of the room. The reason for this is that unlike the tests of West and Reiter, Wheeler did *not* place his origin at one of the major fuel load locations within the room (nor at the doorway). Thus, this test is the first test where the major biases were successfully eliminated. The conclusion has to be that the ATF proposed method has neither validity nor generality.

12. Arc Mapping Applications Which Do Not Require Validation

Several arc mapping scenarios follow directly from accepted science principles and, therefore, do not need validation.

1. *Arc marks are found on some conductor(s)*. This indicates that the circuit was energized at the time of shorting. The conclusion can be reliably made, but will only rarely be of assistance in establishing the origin of a fire.
2. *Multiple arcing which includes a sever-arc*. A conductor has multiple arc marks, but one arc location is a sever-arc. Circuit continuity demands that any arc marks downstream of the sever point had to have occurred before (or simultaneously with) the sever-arc [12, 32]. Note this specifically refers to situations where the hot conductor is severed. If the neutral or ground conductors are severed, but not the hot conductor, then arcing downstream of the sever point might potentially be possible if the hot conductor comes into contact with some other grounded objected, e.g., a water pipe. Further analysis should be done to rule out such contact. (Note that a similar analysis does not pertain to weld-arc locations. While it is certainly true that significant current cannot flow beyond a weld point, a welded conductor represents a bolted short at that location. Consequently, there will also be no arcing upstream of that location, since both conductors are effectively at the same potential),

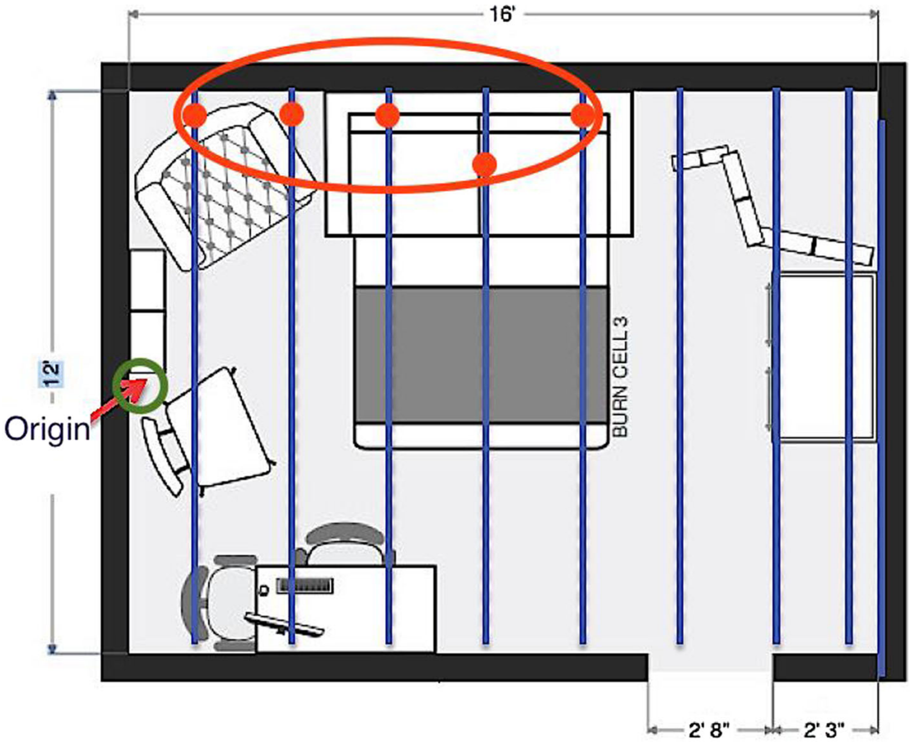

Figure 6. Ellipse plotted according to the ATF recommendation for Wheeler's test No. 3. In this test, the ignition point, the heaviest fuel loads, and the ventilation opening were located at widely separated points. The results show that arcing was found where the heavy fuel was located, not near the fire origin. The area of origin is clearly located not inside the ellipse, but well outside of it.

3. *Two cords, one with welded-short conductors*. Two cords are plugged into one outlet and both cords show arcing, but the conductors on one cord are welded together, while the other cord shows arc marks, but not welded-together conductors. The circuit breaker is tripped. The cord that was welded then necessarily had to be the second event, since if it were first, the circuit breaker would have tripped due to welded-short conditions. This scenario was described by Utt [54].

13. Reliability of Arc Mapping

Churchward and Ryan [18] (Churchward was the Chair of the NFPA Technical Committee on Fire Investigations when arc mapping was first introduced into NFPA 921) pointed out that "Reliance solely on an arc survey to determine the

… proposed area of fire origin places far too much importance on a technique that cannot always be reliable or validated.'' They also noted that if the building is not de-energized relatively quickly, there is likely to be an abundance of arc sites and the imputed 'area of origin' is likely to be huge. They further cautioned that it is not logical to conclude that a circuit where the wire insulation burned up, yet which shows no arcing must have burned only after the power was removed, since exposure of an energized circuit to flaming *may* lead to arcing, but *not inevitably*.

Similarly, Wheeler [30] observed very recently (2015) that ''a great deal has been written about arc mapping,'' however ''there are many factors that influence the reliability of arc mapping [yet] very little has been published that specifically addresses such factors or concerns.'' This is actually an excessively optimistic assessment of the reliability of arc mapping. While more experimental studies might reveal additional information, the existing studies already suffice to indicate that, arc mapping is unreliable and unscientific if a hypothesis is made that abundance of arc beads at a given locale means that fire originated in that area, while a paucity of arc beads indicates that it did not. Only in some narrow circumstances, as discussed above, can sound, technically justified conclusions be drawn from the results of arc mapping.

Wheeler's own tests, even though not numerous, have been important for understanding the reliability of arc mapping, since he has been the only researcher to conduct experiments on the effect of wiring behind protective barriers (Novak [55] presented some theoretical modeling of this situation, but not room fire experiments). Analysis of Wheerler's actual results (but not necessarily his published conclusions) indicates that:

- Significant arcing is likely to be found in areas subjected to ventilation air flows
- Significant arcing is likely to be found in areas of heavy fuel load concentration
- The above two factors tend to dominate the arcing patterns found, and arcing is not likely to be concentrated in the area of fire origin, unless this happens to be an area of heavy fuel load concentration or within the inflow region of incoming ventilation air.

These conclusions are identical to those that can be drawn from Carey's research, albeit quantitatively in the latter case (Appendix 1).

Fire patterns are generally subdivided into two categories [8]: (1) intensity patterns, and (2) movement (direction) patterns. While early researchers hoped that arc mapping would somehow prove to be more indicative than char-depth patterns as far as intensity patterns are concerned, experimental work has not borne this out. Instead, the experimental studies indicate that arc mapping has the same limitations as char-depth studies—local fuel load effects [56] and local ventilation effects [57] are likely to be dominant, and not the location of the fire origin. This is true of *all* the research studies that have been published to date. There is no basis to believe that arc beading will be found to be plentiful in the area of origin, and scarce or absent in areas away from the area of origin. The only exception

would be in cases where fuel load effects and ventilation effects might be successfully excluded, which will require unusual circumstances.

Additional considerations with regards to lack of reliability are the following:

1. In most structures, the majority of building wiring is behind protective membranes, not out in the open. Wheeler's study indicates that arcing patterns behind protective membranes do not bear a significant relationship to the area of fire origin. But even the results of all of the investigators who conducted tests without a protective membrane, if interpreted in an unbiased way, do not suggest that arc mapping is a reliable pointer to the location of the origin of a fire. Carey [26] correctly concluded that arc mapping "is of limited value when the cables are protected from the fire in the initial stages, for example, buried in plaster or installed behind plaster board in cavity walls."
2. Arcing cannot occur where there are no conductors to arc. Most of the experimental studies have been based on a tacit assumption that there is a densely-spaced grid of wiring available for potentially shorting and arcing. This will rarely be true and, in many practical cases, cable runs are sparsely and irregularly distributed. In other cases, a significant grouping of adjacent, parallel circuit cables may be found, often at locales near the load center [58]. Thus, presence of arc beads may indicate mainly where wiring runs were located, rather than revealing anything useful about the progress of the fire.
3. Branch-circuit wiring is often likely to be concentrated below the floor, or in the lowest portions of walls. Generally, fewer circuits are run along ceilings or in the upper portions of walls. Thus, wiring in practice is most likely to be concentrated along the areas where there is least likely to be early fire damage to it. Consequently, experimental studies based on closely-spaced ceiling grids, when applied to such situations, will necessarily present a positive bias.
4. Arcing and shorting may preferentially occur at places where there is a kink or bend in the cable, or a similar stress situation that facilitates shorting of heated wires. No study has explored this.
5. Arcing may occur, but not create an artifact that can be unambiguously associated with arcing [25]. This can also include situations where an identifiable artifact was created, but was subsequently obliterated by fire melting, corrosion, or other fire effects.
6. Few studies exist for arc mapping pertinent to stranded-wire conductors and none for wires inside conduits. However, there is no basis to believe that arc mapping in those situations would be valid under more scenarios than for branch-circuit wiring in NM cables.
7. There have been no validation studies of arc mapping in motor vehicles, which also use stranded wires, but typically have low-voltage DC power supplies and sometimes use circuits with no overcurrent protection.
8. In many cases, the structure will have multiple rooms, and the first task facing the investigator may be to identify the room of origin. No study exists where arc mapping was experimentally studied for a multi-room building. However, there is no basis for assuming that such application would allow valid use of

arc mapping under broader circumstances than is justified for single-room scenarios.

14. Probabilistic Evaluation for Direction Patterns

The main scenario for which valid electrical science allows positive conclusions to be drawn from arc mapping is the severed-wire scenario. For this scenario, probabilities of occurrence can be evaluated, at least for solid-conductor branch circuits. Based on the results of West and Reiter [28] and Carey [16] given above, there is approximately a 5% probability of a second arc on any particular circuit that has arced. The probability is 29% that an arc will be a sever-arc. But conclusions can only be drawn if the non-sever arc is downstream of the sever-arc. Since, in general, there is no bias where the second arc occurs, there is a 50% probability for the downstream location. Thus, the probability is $0.05 \times 0.29 \times 0.5 = 0.0073$, which is 0.73%, that a circuit with arcing evidence will allow the direction of fire movement to be scientifically established on the basis of the presence of a sever-arc. Limited findings suggest that the likelihood may be higher for stranded wire cords, but quantitative estimates are not available.

15. Information Content from Arc Mapping

Fire investigators have at their disposal two more conventional techniques of mapping to establish intensity patterns in fire investigations: char depth surveys and calcination surveys [8]. Both are systematic (and laborious) techniques for making a 2-d or 3-d representation of a fire damage pattern. Arc mapping is not different in principle from either of these two mapping techniques. Quite apart from reliability, discussed above, the information content potentially available from arc mapping should also be considered. A rough estimate suggests that the information content (amount of available data) from an arc map is likely to be about 3 orders of magnitude less than from a char depth or calcination depth survey. Thus, the utility is likely to be exceedingly low. The basis for a 3-orders-of-magnitude estimate can be explained this way: At any one given location, an arc map can only record the presence or absence of an arc bead. By contrast, a char depth survey can include measurements ranging from 0 to, say, 10 mm. Thus, in this regards, there is about 1 order of magnitude more information in the char depth map. But additionally (unlike in some research studies), the fraction of the wall or ceiling surface areas where cables are located may be less than 1%, while there may be close to 100% of surfaces where wood members are located which are amenable to char depth surveying. This means that there are 2 orders of magnitude less information from the arc map, with regards to area of coverage. Thus, there can be about 3 orders of magnitude less information potentially available from an arc map than from a char depth survey.

16. Conclusions

Procedurally, arc mapping is a technique for plotting locations of arc marks on a floor plan (map) of a building. As such, it is non-controversial, assuming that the arcs (or absence thereof) are correctly identified and plotted. Conclusions drawn from an arc map, however, may be unreliable and inconsistent with known science, depending on the inferences being drawn. Additional hypotheses are needed to enable any non-trivial conclusions to be drawn, and these hypotheses must have been demonstrated to be valid, for the work to be credible.

Once an arc map is prepared, in a small fraction of cases, reliable conclusions can be drawn from applying basic principles of electricity, especially the fact that arcing cannot occur without current flow, and current cannot flow in circuits beyond a sever or weld point, or if a circuit breaker has tripped. But in the majority of cases, principles of science do not allow conclusions to be drawn from an arc map with regards to the origin of the fire. Experimental research may also justify some hypotheses, but this has to be successfully demonstrated.

Delplace and Vos proposed that the arc mapping method should be considered as being based on two hypotheses: (1) that patterns of arcing will be spatially similar to patterns of combustion damage; and (2) a rather confusing hypothesis which implies that arc sites will be found predominantly near the fire origin. It can be concluded that hypothesis #1 is generally true, but also generally unhelpful. Concerning hypothesis #2, other researchers, along with many practitioners, have more succinctly assumed that arc marks will be copious near the area of fire origin, and scant otherwise. This assumption is not a deduction from any principles of science, and would only potentially be true if shown to be so on the basis of experimental testing.

To consider the results from experimental testing, it must first be understood that an arc map is a documentation of a type of fire pattern, and all fire patterns are divided into two main categories—direction patterns, and intensity patterns. Research has identified only one situation where a direction pattern may be properly established on the basis of an arc map. If there is a sever-arc, and a further arc downstream of that, then the direction of fire attack has to be such that the downstream location arced prior to the upstream, sever-arc location. But analysis of test data has shown that this situation is likely to occur in less than 1% of branch circuits attacked by fire.

Intensity patterns (for any type of fire pattern) are likely to be governed by three main variables: (1) local fuel load effects; (2) ventilation effects; and (3) burning duration. Only the latter has any potential correlation to the location of the fire origin (since if ventilation and fuel loading were uniform throughout, the place of fire origin would necessarily be the place where the fire burned the longest). But in most cases, ventilation and fuel load effects are highly non-uniform. Consequently, these variables are likely to dominate the outcome of arcing. There is only one study which provided sufficient data to allow some quantitative conclusions to be drawn. In the case of Carey's 2009 study (Appendix 1), only 23% of the arc beads were found near the area of fire origin, while 61% were found near heavy fuel concentration, 51% were located near localized ventilation, and 3% were found elsewhere

(note that the numbers do not add to 100%, since—apart from 'elsewhere'—an arc bead location may fall into more than one category). The experiments of other researchers are broadly consistent with these findings, even though their modest number of tests do not make them suitable for a statistical data treatment. A method cannot be considered to be reliable, if it produces true results in only a minority of instances.

Inside habitable buildings, wiring is occasionally placed in the open, unprotected. But predominantly, building wiring is located behind protective layers such as plaster, wallboard, or masonry. Such protective layers will inhibit early thermal attack on the wiring. They will also even out the temperature gradients, so that failure of wiring should be expected to begin only when the fire has become widespread, instead of still being localized near the area of origin. Consequently, if the actual wiring is behind protective layers, experiments that are based on unprotected installations innately have a bias towards positive findings. Carey's tests were done with no gypsum wallboard cover, and such results will be unconservative with regards to any situations where gypsum wallboard, or another form of thermal protection barrier, exists. In fact, only one test, by one researcher, has been reported where the tested wiring was protected by a gypsum wallboard.

Significant experimental research has only been done on solid-core, branch-circuit cable conductors. Research conducted on stranded wire arcing has been minimal. In the US, wiring in commercial buildings, but not residential ones, is usually required to be located inside conduits; but in a few locales, all electric wiring is required to be in conduits. Conduits have traditionally been metallic, although in some cases plastic conduits are also used. There have been no experimental data on the arcing patterns in buildings within conduits. For the sake of completeness, it is desirable that research be done on arcing of stranded wires, and also on arcing inside conduits. It is further recommended that, for NM wiring, research be done with gypsum wallboard protection, using fully Code-compliant wiring methods. However, since gypsum wallboard and metal conduits serve to diffuse the fire's thermal attack over a larger area, it is highly unlikely that this research would increase the range of conditions under which results from arc mapping may be used to make reliable conclusions.

Arc mapping is used almost exclusively for forensic purposes. Forensic techniques should not be utilized unless there is a sound science basis to them, and research has established that the technique is reliable. With regards to techniques which are not a direct expression of accepted principles of science, it is not acceptable to use methods considered to be promising, commonly-used, or potentially helpful, if their reliability has not been established.

Functionally, arc maps present information organized in the same manner as for a char depth survey or a calcination survey. But there is about 3 orders of magnitude less information potentially recordable in an arc map than in the char depth or calcination survey. Thus, even if used legitimately, an arc map conveys greatly less information than fire scene surveys based other types of damage patterns.

Some authors have published conclusions that are at variance with their data. The fact that some experiments show a presence, or even a copious presence, of

arcing in the vicinity of the area of ignition does not logically indicate that arc mapping can distinguish between areas of fire origin and areas where fire did not originate, if copious arcing is also found in areas away from the area of fire origin.

The following hypotheses are not supported by science or reliable experimental data (that is, they are myths):

- An abundance of arc beads at a given locale means that fire originated in that area, while a paucity of arc beads indicates that it did not.
- When multiple arcs are present on a circuit, the direction of arcing will necessarily proceed upstream towards the power source.
- If an appliance is the victim of a fire, internal arcing will be primarily near the exterior of the unit, while arcing deep inside indicates a fire origin at that place.

In fire investigation reports, it is not acceptable for an investigator to report that a conclusion was based simply on "arc mapping." There are few circumstances where arc mapping may be utilized in a scientifically reliable manner. A fire investigator wishing to rely on arc mapping in a fire investigation report must explicitly set forth a valid governing hypothesis, and demonstrate how the analysis comports with that hypothesis.

It is recommended that NFPA 921 be revised to eliminate arc mapping as one of the four main methods for establishing fire origin, and to subsume it under the more general category of "fire patterns." In addition, it is important that NFPA 921 reduce the implied general utility of the method and provide more explicit discussion of its limitations and of those circumstances where arc mapping is a valid method for assisting in the determination of a fire origin.

Appendix 1: Analysis of Carey's (2009) Data

Due to the large number of tests reported (22 room tests with single fire ignition), a statistical analysis is possible of Carey's data; this is shown in Table 2. Note that, apart from 'Elsewhere,' the categories are not exclusive. For example, an arc bead may occur both near the fire origin and near a ventilation source. Thus, for any given experiment, the totals may add up to more than 100%.

The following conclusions may be drawn from these data:

1. The dominant factor determining the likelihood that an arc bead will be found at a given locale is fuel load.
2. Ventilation is the second most likely cause for arc bead formation
3. The likelihood that an arc bead will be found at a given location due to this being the location of fire origin is only 1/3 to $\frac{1}{2}$ that due fuel load or ventilation reasons.
4. The likelihood is very small that an arc bead will be formed at locales not near heavy fuel, not near ventilation inflow path, and not near the fire origin.
5. The data do not support the hypothesis that the most likely reason for finding an arc bead at a given locale is that the location is near the fire origin.

Table 2
Arc Beads Found by Carey in the Experiments Having Only a Single Fire Origin

Exp. No.	Arc beads near origin	Arc beads near heavy fuel	Arc beads near ventilation sources	Elsewhere	Total arc beads
1	1	2	2	0	4
4	0	1	0	0	1
7	1	3	3	0	4
8	2	4	1	0	4
10	2	3	2	0	3
16	1	3	1	0	4
17	1	3	5	0	6
21	0	3	2	1	4
22	1	2	1	0	4
23	1	3	1	0	4
24	1	2	2	1	6
26	1	1	2	0	3
27	1	0	2	0	3
29	0	2	3	0	5
30	0	4	1	0	4
31	1	1	4	0	4
33	1	2	2	0	4
34	1	2	3	0	4
35	2	2	1	0	5
37	1	2	1	1	3
38	1	4	1	0	4
39	0	5	5	0	5
Sum	20	54	45	3	88
Percent	22.7	61.4	51.1	3.4	100.0

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